Searching for the Earliest Galaxies using the Gunn-Peterson Trough and the Lyman Alpha Emission Line

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ABSTRACT

If the universe was reionized by O and B stars in an early population of galaxies, the associated supernovae should have enriched the universe to a mean metallicity $\bar{Z} = 10^{-5}(1 + n_{rec})$, where n_{rec} is the mean number of times that each baryon recombined during the reionization era. This is consistent with recent observations of the metallicity in the Lyα forest at $z \simeq 3$. The mean surface brightness observable at present from the galaxies that produced these heavy elements, in the rest-frame wavelengths 1216Å $< \lambda \lesssim$ 2500Å, should be $\sim 10^{-6}(\bar{Z}/10^{-4})(\Omega_b h^2/0.02)$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{arcsec}^{-2}$. Most of this radiation should be emitted at $z > 5$, before reionization was complete.

These high-redshift galaxies may be detectable in near-infrared photometric surveys, identifying them via the Gunn-Peterson trough (analogous to the use of the Lyman limit cutoff to search for galaxies at $z \sim 3$, where the Lyα forest blanketing is smaller). Their spectrum may also be characterized by a strong Lyα emission line. However, the spectra of galaxies seen behind intervening gas that is still neutral should show the red damping wing of the Gunn-Peterson trough, with a predictable profile that obstructs part of the Lyα emission.

The low-mass galaxies formed before reionization might constitute a distinctive population; we discuss the signature that this population could have in the faint number counts. Although most of these galaxies should have merged into larger ones, those that survived to the present could be dwarf spheroidals.

Subject headings: galaxies: formation - large-scale structure of universe - quasars: absorption lines

1. Introduction

Observations of large-scale structure have, over the last few decades, strongly supported hierarchical models of gravitational instability with "cold dark matter". Density fluctuations grow to non-linearity first on small scales. High-density halos are formed, which then continue to accrete

low density matter around them and merge with each other to form objects on progressively larger scales. Evidence for this general picture includes the observed hierarchical nature of galaxy clustering and the galaxy peculiar velocity field (e.g., Strauss & Willick 1995), the presence of substructure in galaxy clusters showing that clusters are being assembled at the present time from smaller units (e.g., Bird 1994), the Lyα forest at high redshift showing that structures on smaller scales than the present clusters were collapsing in the past (Rauch et al. 1997 and references therein), and the CMB fluctuations (White, Scott, & Silk 1994). Even though the origin of the initial fluctuations and the nature of the dark matter remain in the realm of speculation, and the exact form of the linear power spectrum of density fluctuations is uncertain, a generic consequence of this scenario is that the first galaxies to form in the universe had very small scales and masses. The earliest galaxies should have formed in the first collapsed objects where the baryonic component was able to lose its energy through radiative cooling, concentrating to the center of dark matter halos and becoming self-gravitating, leading to the formation of the first stars. In the absence of cooling, the gas virialises and remains in hydrostatic equilibrium in dark matter halos and galaxies cannot form (e.g., White & Rees 1978 and references therein).

As more massive structures form, the velocity dispersion of collapsed halos increases, as does the temperature of the gas in these halos. The gas that forms the first galaxies is, of course, initially neutral. For $T \lesssim 5 \times 10^3$ K, the only effective coolant in gas with the primordial composition of hydrogen and helium is molecular hydrogen (e.g., Tegmark et al. 1996). Molecular cooling almost certainly played a role in forming the very first stars, but the fraction of molecules is always small and they should be rapidly photodissociated by UV photons from the stars themselves (Haiman, Rees, & Loeb 1997; Ostriker & Gnedin 1997). Radiative cooling is then suppressed until temperatures $\sim 10^4$ K are reached, when atomic hydrogen provides efficient cooling through line excitation and collisional ionization by electrons in the Maxwellian tail of the energy distribution. The cooling rate rises steeply with temperature, so the gas in this regime contracts almost isothermally.

The first-generation galaxies will eventually provide enough UV photons to ionize all the diffuse gas in the universe (e.g., Couchman & Rees 1986); active nuclei could also start forming and contribute to the process of "reionization"(e.g., Arons & Wingert 1972). The total amount of star formation that precedes reionization obviously depends on the IMF; it also depends on what fraction of the Lyman continuum from O and B stars escapes into the intergalactic medium, rather than being absorbed by gas in the star-forming regious themselves. After reionization has occurred, there is a universal UV background high enough to maintain the HI fraction of any diffuse gas at a very low level; this substantially reduces the cooling rate at temperatures below $\sim 5 \times 10^4$ K. This ionized diffuse gas can form the structures responsible for the observed Lyα forest (Cen et al. 1994, Miralda-Escudé et al. 1996, hereafter MCOR, and references therein). The higher entropy of the ionized gas, together with the suppressed cooling rate, inhibit its infall into halos with virial temperatures much below 10^5 K (e.g., Efstathiou 1992; Thoul & Weinberg 1996); dissipation is only efficient in more massive objects, and presumably leads to the formation of

most galaxies that we have observed at all redshifts back to $z \lesssim 5$.

The physics of the galaxy formation process is probably substantially different depending on whether they form from neutral or from photoionized gas, and this suggests that galaxies formed in two distinct phases (e.g., Haiman & Loeb 1997a). In this paper, we shall designate "Population A" those galaxies formed from accretion of photoionized gas, and "Population B" those galaxies formed in the absence of an external ionizing background, so that photoionization from external sources was negligible during the dissipation process. Essentially, the Population B formed before the reionization epoch and emitted the photons that reionized the universe, and the Population A formed afterwards, although in practice reionization is a gradual process where different regions will be photoionized at different times, as they are immersed in expanding cosmological HII regions that eventually overlap.

The distinction between these two populations is so far only a theoretical concept, and our understanding of the effects of reionization on galaxy formation is likely to remain limited until the existence of the Population B (hereafter, Pop B) can be observationally tested. In this paper we discuss the constraints that we can put on the characteristics of the Pop B galaxies given our present knowledge of the high redshift universe, and the prospects for their detection. In a previous paper (Miralda-Escudé & Rees 1997, hereafter MR97), the possibility of detecting individual supernovae from these galaxies was investigated, pointing out that although supernovae at $z \gtrsim 5$ should be extremely faint, their host galaxies could be even fainter, given the small masses expected for the Pop B galaxies. But as we shall see here, the luminosities of Pop B galaxies may in fact be not much lower than that of a supernova. Moreover, their detection is facilitated because they should be exceedingly numerous, and because of the distinct spectral signature expected from starburst galaxies at high redshift: the Gunn-Peterson trough and a possibly strong Lyα emission line.

2. The Brightness of Stellar Radiation Emitted at Reionization

It has recently been shown that the gas in the Lyα forest was already enriched to a heavy element abundance $Z \sim 10^{-2} Z_\odot$ by a redshift $z = 3$, from observations of absorption lines of CIV and other species associated with Lyα forest lines with $10^{14.7}\,\mathrm{cm}^{-2} < N_{HI} \lesssim 10^{16}\,\mathrm{cm}^{-2}$ (Songaila & Cowie 1996 and references therein). Detailed calculations of the expected column densities of the observed absorption lines, using hydrodynamic simulations of the Lyα forest and realistic models for the spectrum of the ionizing background (Rauch, Haehnelt, & Steinmetz 1996; Hellsten et al. 1997) have shown that the carbon abundance needed to reproduce the observations is [C/H] $= -2.5$. The metal abundances are similar to those of Population II stars, where oxygen is the most abundant element and is overabundant by a factor ~ 2 relative to carbon. With $Z_\odot = 0.02$, the metallicity of the Lyα forest is then $Z \simeq 10^{-4}$. As argued in MR97 this metallicity should be approximately the same as the mean metallicity of the universe at $z = 3$ if the Lyα forest contains most of the baryons (as is found to be the case in models of structure formation

for the Lyα forest similar to those analyzed in Hernquist et al. 1996 and MCOR), and if the Lyα forest metallicity is uniform. Actually, the metallicity probably increases with N_{HI}: Hellsten et al. (1996) find that the absorbers with $N_{HI} < 10^{15}\,\mathrm{cm}^{-2}$, which should contain a large fraction of the baryons, should have lower metallicity than [C/H] $= -2.5$, the value they need to account for the CIV column densities of absorbers with higher N_{HI}. The increase of metallicity with N_{HI} is also predicted in models of the enrichment of the IGM (Gnedin & Ostriker 1997). This can result in a lower mean metallicity. In fact, Songaila (1997) has shown that by adding the column density of the CIV lines, the lower limit to the mass of metals that is obtained is smaller by a factor ~ 10 compared to the value we assume here. Thus, significant uncertainties still remain on the mean metallicity.

The ratio of the mass of heavy elements ejected by a star to the energy in ionizing photons emitted over the lifetime of the star, as derived from models of stellar evolution and supernova explosions, turns out to be about constant over the relevant mass range $10M_\odot \lesssim M \lesssim 50M_\odot$ according to stellar evolution models (although the possibility that some massive stars collapse to black holes without ejecting heavy elements introduces some uncertainty), so given a mean metallicity $\bar{Z}$ we can predict the energy in ionizing photons that was emitted for each baryon in the universe. According to Madau & Shull (1996), this energy is $0.002\bar{Z}m_pc^2$ per baryon. As discussed in MR97, for $\bar{Z} = 10^{-4}$ we find that 10 ionizing photons were emitted per baryon by the stars that produced the Lyα forest heavy elements (assuming a mean energy of 20 eV per ionizing photon). This is probably the radiation produced by the Pop B galaxies, although it is certainly possible that after the universe was reionized, some of the heavy elements produced in the newly forming, more massive Pop A galaxies were also dispersed to the intergalactic medium (hereafter, IGM) and contributed to the Lyα forest metal abundance.

One of these 10 ionizing photons was used to reionize the universe. The majority of the other photons must also have been absorbed by neutral hydrogen. A fraction f_i of the photons will be absorbed internally, in the galaxies where the emitting stars were formed; the rest should be absorbed after having escaped their original galaxies, in other dense absorbing systems where protons can recombine many times during the reionization epoch (similar to the observed Lyman limit systems). Of the photons that were absorbed internally, about 70% resulted in the production of a Lyα photon, and the other 30% resulted in emission in the two-photon continuum from the 2s state (see Table 9.1 in Spitzer 1978; we assume that the internal absorption takes place in regions that are sufficiently optically thick to absorb essentially all ionizing photons produced by direct recombination to the ground state). The Lyα photons will then be scattered many times in the host galaxy, until they move to the wings of the Lyα line and escape. Some of them may be absorbed by dust before escaping, so we define f_d as the fraction of Lyα photons that can eventually escape without being absorbed by dust. The mean comoving number density of these Lyα photons is then $7\,f_i f_d(\bar{Z}_{-4})n_b$, where n_b is the comoving baryon density and $\bar{Z}_{-4} = \bar{Z}/10^{-4}$. The mean surface brightness of the Lyα emission line from the Pop B galaxies is simply obtained by multiplying the photon comoving number density by $c/4\pi$, which yields

$10^{-7} f_i\, f_d\, \bar{Z}_{-4}(\Omega_b h^2/0.02)$ photons cm^{-2} s^{-1} arcsec^{-2}). The fiducial value of $\Omega_b h^2$ used here is close to that implied by a primordial deuterium abundance $D/H \simeq 3 \times 10^{-5}$, as reported by Tytler, Fan, & Burles (1996).

This determines the average surface brightness we receive in the sky from these Pop B galaxies in the Lyα emission line, or in other words, the product of the number of Pop B galaxies per solid angle times their individual, mean Lyα flux. A much more uncertain question is the flux from each individual galaxy; the uncertainty is essentially tied to the efficiency of forming massive stars in collapsed dark matter halos as a function of their velocity dispersion during the reionization epoch. To see the range of possibilities we might have for the main characteristics of Pop B galaxies, we shall examine three possible scenarios:

(a) Star formation is highly efficient in all collapsed halos with velocity dispersion $\sigma \gtrsim 15\,\mathrm{Km\,s^{-1}}$, corresponding to the virial temperature $T = \mu\sigma^2/k \simeq 10^4$ K where rapid cooling by atomic hydrogen can start taking place. In this case, reionization would take place as soon as the highest density peaks on the scales of these low velocity dispersions collapse. As a specific example, let us take the top-hat spherical collapse model for a halo, where a spherical region of mass M turns around at a radius R_t when the age of the universe is $t_f/2$, and collapses at time t_f (e.g., Peebles 1980, §19), forming an isothermal halo with $\sigma^2 = GM/R_t$ (obtained assuming that a mass M is contained within a radius $R_t/2$ in the final equilibrium configuration). The halo mass is then $M = 2^{3/2}/(2\pi G)\sigma^3 t_f \sim 10^9 M_\odot(\sigma/20\,\mathrm{Km\,s^{-1}})^3\,(t_f/10^9\,\mathrm{yr})$. If a fraction f_b of the mass turns to stars (with f_b close to Ω_b for the high efficiency case) over a timescale $t_s \sim 0.3 t_f$ of order the free-fall time of the halo, the star formation rate is $0.3 M_\odot\,\mathrm{yr}^{-1}(\sigma/20\,\mathrm{Km\,s^{-1}})^3\,(f_b/0.1)$. For a normal IMF, this can yield a luminosity close to the peak luminosity of a supernova. The implied metal production rate depends of course on the IMF, but is $\sim 10^{-2}$ times the star formation rate when we calibrate it from the observed yields in normal galaxies where the average metallicity is $\sim$ 1% after a large fraction of the gas has turned to stars. Given the numbers discussed above for the luminosity in Lyα photons, which imply that $10^5\, f_i\, f_d$ Lyα photons are emitted for each baryon that is expelled from stars in the form of heavy elements, the Lyα luminosity from this efficient, rapid starburst in a Pop B galaxy would be $10^{52}\, f_i\, f_d\,(\sigma/20\,\mathrm{Km\,s^{-1}})^3\,(f_b/0.1)$ photons s^{-1}. The corresponding Lyα flux at present (for $\Omega = 1$ and $H_0 = 50\,\mathrm{Km\,s^{-1}\,Mpc^{-1}}$) is $5 \times 10^{-7}\, f_i\, f_d\,(\sigma/20\,\mathrm{Km\,s^{-1}})^3\,(f_b/0.1)\,\left[1-(1+z_f)^{-1/2}\right]^{-2}\,(1+z_f)^{-1}$ photons cm^{-2} s^{-1}. If the sources that reionized the universe have these characteristics, then we can use the mean Lyα surface brightness we obtained earlier to conclude that the number density of these sources in the sky should be ~ 1 per arcsec^2 for the fiducial numbers we have chosen, and a formation redshift $1 + z_f \sim 10$. The redshift z_f should of course depend on the detailed model for the amplitude of the primordial fluctuations on small scales.

The main problem with this scenario is that, as pointed out by several authors (e.g., Dekel & Silk 1986), the energy from supernova explosions in galaxies of such low velocity dispersions should easily be able to expel the gas from the halo when only a small fraction of the gas has turned to stars. In fact, the enriched gas needs to be expelled at some stage to spread the heavy

elements through the IGM. Although one could imagine the supernovae taking place in a very dense medium where the energy was quickly radiated as soft X-rays, it seems likely that the supernova explosions will reduce the efficiency of star formation by a large factor, due to the heating and expulsion of gas. Indeed, it has been argued that this reduction of the star formation rate is necessary to prevent too many baryons from turning to stars in small galaxies at early times (e.g., Navarro & Steinmetz 1997). This leaves us with two other types of Pop B galaxies that could be the sources of the reionization photons, our scenarios (b) and (c).

(b) Reionization is caused mostly by low-mass objects similar to case (a), but only a small fraction of the gas in each object turns to stars before the gas is expelled in a wind. Thus, the parameter $f_b \ll \Omega_b$, so each Pop B galaxy emits fewer photons and a larger number of them have to form, which therefore have to originate from lower amplitude peaks. The luminosity of each galaxy would be reduced proportionally to f_b due to the smaller mass of stars. This might be partly compensated by having starbursts of very short duration (in principle, starbursts could occur over a time much shorter than the free-fall time through the dark matter halo if only a small fraction of the halo gas turns to stars).

(c) The efficiency of massive star formation in the first halos where atomic cooling takes place is so low that not enough photons are emitted to complete the reionization until more massive galaxies (with $\sigma \gtrsim 100\,\mathrm{Km\,s^{-1}}$ collapse and form stars more efficiently. In this case, the Pop B galaxies responsible for the reionization would have relatively large masses, well above the Jeans mass for photoionized gas, so reionization might be of little consequence for the process of galaxy formation, and the Pop B galaxies might not have any observational characteristic that would distinguish them from Pop A galaxies (this is because photoionization has little effect on the cooling rate in halos with velocity dispersion $\sigma \gtrsim 100\,\mathrm{Km\,s^{-1}}$; see Thoul & Weinberg 1996, Navarro & Steinmetz 1997).

The inefficiency of star formation in low σ galaxies might arise from two different reasons. One is the rapid expulsion of the gas after a very small number of stars have formed, as in case (b). The other possibility is that the gas is not expelled at all, but instead forms rotationally supported disks by radiative cooling and dissipation, and then the gas in these disks stays in atomic form and does not effectively turn to stars. This could happen because the low-metallicity gas might not cool to the cold phase of the interstellar medium (see Corbelli & Salpeter 1995). Staying at a temperature $T \simeq 5000$ K in a disk with a low circular rotation velocity, the disks might be gravitationally stable according to Toomre's criterion, preventing the formation of molecular clouds. These stable disks might persist until their host halos merge within larger systems, when the disks would be disrupted and the gas would again dissipate and form a new, more massive disk, with a higher efficiency of star formation. A low star formation efficiency in low σ galaxies could also be part of the solution to the common problem that hierarchical models have in producing too many low-mass galaxies (e.g., Kauffmann, Guiderdoni, & White 1994).

We need to point out here that moderately massive galaxies are likely to form during

reionization, even in cases (a) and (b), because the power spectrum at small scales in cold dark matter models generically flattens to a slope close to $n = -3$, so the amplitude of fluctuations decreases very slowly with scale. As an example, let us consider the standard cold dark matter model with $h = 0.5$, and the rms density fluctuation normalized at present to $\sigma_8 = 0.7$ on spheres of $8h^{-1}$ Mpc. This model has been shown to be approximately in agreement with the observed characteristics of the Lyα forest (Hernquist et al. 1996, Davé et al. 1997, Rauch et al. 1997), and therefore should probably have about the right amplitude of density fluctuations on small scales. The three solid lines in Figure 1 show the velocity dispersion (or virial temperature $T_{vir} = \mu\sigma^2/k$) of halos having collapsed from (1,2,3)-σ fluctuations as a function of redshift (assuming $\delta_c = 1.69$ for the critical value of the linear overdensity that corresponds to the formation of a galaxy, as in the spherical collapse model). The dashed lines indicate constant halo mass. If, for example, reionization was complete at $z \simeq 9$, when halos with $\sigma = 20\,\mathrm{Km\,s^{-1}}$ would just be collapsing from $2-\sigma$ peaks, at the same epoch we would have halos with $\sigma = 75\,\mathrm{Km\,s^{-1}}$ (with a mass ~ 50 times larger than halos with $\sigma = 20\,\mathrm{Km\,s^{-1}}$) collapsing from $3-\sigma$ peaks on this larger scale. In a Gaussian theory, the $3-\sigma$ peaks should contain $\sim 10\%$ as much mass as the $2-\sigma$ peaks at a fixed epoch, so we see that the mass distribution of the Pop B galaxies should probably extend well above the minimum mass for efficient atomic cooling. Notice that the very large range in mass of collapsed objects at high redshift is a generic consequence of the flattening of the power spectrum on small scales, due to the fact that the universe was radiation dominated when these small scales entered the horizon. Objects from 1-σ peaks, which contain most of the mass, probably never cooled before reionization because they were ionized by the radiation from more massive objects, and could only start collapsing at $z \simeq 3$, at $\sigma \simeq 30\,\mathrm{Km\,s^{-1}}$, when the cooling rate was again fast enough. But objects from 3-σ peaks at $z = 9$ could already have total masses over $10^{10} M_\odot$.

3. Detecting Galaxies at $z > 5$

We now discuss the prospects for detection of this population of galaxies at high redshift. First, we notice that given the mean surface brightness of Lyα photons derived previously, the surface brightness in the UV continuum also follows with relative little additional uncertainty, because the stars emitting most of the light in the range $1216\text{Å} < \lambda \lesssim 2500$ Åare also mostly very young stars. Given the typical UV spectrum of a starburst (e.g., Fig. 1 in Bruzual 1983), we infer that for every Lyα photon produced from ionizing photons there should be ~ 10 UV continuum photons (because the energy emitted in ionizing photons is $\sim 1/3$ of the UV energy emitted to the red of Lyα in a young starburst, and 1/3 of the energy in ionizing photons is converted to Lyα photons). This implies that the mean surface brightness from all Pop B galaxies in the rest-frame UV continuum is 10^{-6} photons $\mathrm{cm^{-2}\,s^{-1}\,arcsec^{-2}}$. The value of this mean surface brightness agrees with the calculation by Haiman & Loeb (1997b), who used also the metallicity of the Lyα forest as a constraint and made a more detailed model of the stellar population and the distribution of galaxy luminosities.

The main spectral feature that should identify any such galaxies at $z \gtrsim 5$ is a sharp break of the UV continuum at the Lyα wavelength, due to the Gunn-Peterson trough (Gunn & Peterson 1965); in addition, the Lyα emission line may be present, depending on internal dust absorption and scattering of the Lyα photons (see the next section). Notice that the redshift at which the IGM was reionized is not highly relevant regarding the presence of the Gunn-Peterson trough, because even if the medium was reionized at $z \gg 5$, we know that the flux decrement caused by the Lyα forest reaches a factor of 2 at $z \simeq 4$ and grows rapidly with redshift. Thus, the technique of identifying galaxies at $z \simeq 3$ from the Lyman continuum break (Guhathakurta et al. 1990; Steidel et al. 1996) should be replaced by the Gunn-Peterson trough at $z \gtrsim 5$ (see Madau 1995 and Madau et al. 1996 for a careful analysis of the effects of the Lyα forest on galaxy colors), although some residual flux between the Lyα line and the Lyman limit would still be present up to $z \simeq 7$ if the reionization occurred earlier, and the Lyman limit discontinuity may then be used in conjunction (see Loeb & Haiman 1997).

The mean surface brightness in the rest-frame UV continuum from the Pop B galaxies can also be expressed as $S_\nu = 6 \times 10^{-33}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,arcsec^{-2}} = 32\,\mathrm{AB\,arcsec^{-2}}$ (where AB denotes AB magnitudes in the band where the UV continuum is observed; notice that in these units, the derived surface brightness is also independent of redshift because the $(1+z)$ factor due to the redshift of the photons is cancelled since we express the surface brightness in energy per unit frequency). Here we have adopted the values $\Omega_b h^2 = 0.02$, $\bar{Z} = 10^{-4}$; the surface brightness is of course proportional to these two quantities. If we now take the example of case (a) in the last section, where there is one Pop B galaxy per arcsec^2 at redshifts $z_f \sim 10$ with $\sigma \simeq 20\,\mathrm{Km\,s^{-1}}$ (corresponding to 2-σ peaks in Fig. 1), each such galaxy would have an AB magnitude of 32. However, as mentioned earlier, realistically these high-z galaxies should have a wide range of luminosities, corresponding to the range of their masses. The dotted lines in Figure 1 indicate the AB magnitudes of galaxies in halos during a starburst, under the same assumption as in §2 that all the baryons turn to stars over the time $t_s \sim 0.3 t_f$. The AB magnitude is for rest-frame wavelengths in the UV continuum, longward of Lyα . Thus, galaxies forming from $3-\sigma$ peaks could have AB magnitudes of 28 even at $z \sim 10$. Even though these would be ~ 500 times more rare than $2-\sigma$ peaks at the same redshift, the number density could still be close to one galaxy per square arc minute. Our scenarios (b) or (c) would be more optimistic because, for a fixed epoch of reionization, a model with a higher amplitude of density fluctuations and a greater number of massive halos at high redshift would be required due to the lower overall efficiencies of star formation and production of ionizing photons.

These high-redshift galaxies will probably be detectable soon. Detection with ground-based telescopes is hindered by the high sky background in the infrared, but may still work at $z \lesssim 6$, and in Lyα searches where special wavelengths with low atmospheric emission are chosen. The Keck telescope can detect point sources to AB magnitudes $R < 28$, and $I < 27$, in a night of observing time (M. Rauch 1997, priv. communication; Cohen 1995a,b). The magnitude limit could be improved with adaptive optics. With space instruments, the faintest galaxies in the HDF reach

to $I \simeq 28.5$ (Williams et al. 1996). The *New Generation Space Telescope* could image galaxies to AB magnitudes ~ 31 in the near-infrared, and should be able to detect galaxies to much higher redshift (Mather & Stockman 1996), with a much higher number density than has been seen so far. The prospect for detecting the high-redshift galaxies responsible for the enrichment of the Lyα forest has also been analyzed in Haiman & Loeb (1997b), Loeb & Haiman (1997), Loeb (1997) and Cen (1997).

In general, the lensing magnification in rich lensing clusters may be used here to stretch the magnitude limit (see also Cen 1997). As an example, a lensing cluster with an Einstein ring radius $b = 30''$ should magnify to $A > 10$ an area of ~ 30 arcsec^2 in the source plane. In the example used above, about 30 galaxies with $AB = 32$ could be in this area, which would be magnified to $AB = 29.5$. Magnified images of high-redshift galaxies should characteristically appear in pairs around the critical lines, in a region that can be predicted from lensing models (see Miralda-Escudé & Fort 1993; Kneib et al. 1996, and references therein), so this should help in their identification. These numbers indicate that a new deep field (similar to the HDF) imaged with HST in a rich cluster, adding also the H and J filters in the near-infrared, might well identify several galaxies at $z > 5$. In fact, the largest redshift object known at present (at $z = 4.92$) is already a gravitationally lensed galaxy (Franx et al. 1997).

We have assumed in this discussion that these high-redshift galaxies would be sufficiently small to remain unresolved. Resolved object would need to have higher fluxes to be detected, since the detection is limited by the sky background. The scale-lengths of the Pop B galaxies are expected to be very small. The radius of a collapsed halo scales as σt_f. Compared to present day galaxies, the Pop B galaxies at $z > 5$ should have a formation time smaller by at least a factor ~ 10, and a velocity dispersion that is also smaller by a factor ~ 5. We can reasonably assume that the ratio of the size of the region where stars form to the radius of the collapsed dark matter halo is similar for all types of galaxies, if the processes of dissipation and distribution of the angular momentum that determine the size of rotating disks (Fall & Efstathiou 1980), or the onset of star formation in spheroidal components when a gas cloud becomes self-gravitating and fragmentation occurs, are similar in galaxies of different masses. Therefore, given the typical scales of a few Kpc for present-day galaxies, the scales of Pop B galaxies are likely to be smaller than 100 pc, corresponding to angular sizes ~ 0.01 arcsec. This would remain unresolved even with NGST.

4. The Lyman Alpha Emission Line

Another possible way to detect the faint Pop B galaxies is to search directly for the Lyα emission line. As we discussed before, for a normal starburst spectrum we expect $\sim 10\%$ of the UV photons to be in the Lyα emission line if dust absorption is not important. Therefore, if the sensitivity for detecting galaxies is still limited by the sky background for emission-line searches, the width of the line should be $\Delta\lambda/\lambda < 0.01$ to allow detection on a shorter time than for the UV continuum. The width of the Lyα line in emission from a region of neutral gas with column density

$N_{HI} = 10^{22} N_{22}\,\mathrm{cm}^{-2}$, and velocity dispersion $\sigma = 10\sigma_6\,\mathrm{Km\,s}^{-1}$ is $\Delta\lambda/\lambda \simeq 2\times 10^{-3}(N_{22}\sigma_6)^{1/3}$ (Harrington 1973; this formula is valid for a very optically thick system where photons are scattered many times in the damping wing before escaping from the system). Thus, the sensitivity of emission-line searches might be at best similar to searches for the UV continuum, if the sky background were smooth in wavelength.

From the ground, line-emission searches have the advantage that a wavelength of particularly low atmospheric emission can be selected, so the line-emission search can then be substantially more sensitive than a photometric one. The deepest Lyα emission surveys so far have reached limits of 3×10^{-6}photons$\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $z \sim 4$ (Thompson, Djorgovski, & Trauger 1995), and 10^{-4}photons$\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $z \sim 7$ (Parkes, Collins, & Joseph 1994). With our assumed ratio of 10 UV continuum photons for each Lyα photon (and ignoring the possibility of dust obscuration), these limits correspond to AB magnitudes of 28 and 24.5 in Figure 1, respectively. At $z \sim 4$, the population of luminous starbursts must be obscured by dust, as shown by the recent discovery by Steidel et al. (1996) of the Lyman limit dropout galaxies with $AB \sim 26$ at this redshift. But the lower mass galaxies at higher redshift might have stronger Lyα emission lines. Some examples of high redshift galaxies with strong Lyα emission have been found (Hu & McMahon 1996; Franx et al. 1997).

The Lyα emission line may be suppressed due to internal dust extinction. In addition, any photon emitted in the blue side of the Lyα line will be scattered in the surrounding IGM, reducing the strength of the line by a factor of 2. For a galaxy observed when the surrounding IGM is still mostly neutral, even photons on the red side can be scattered due to the damping wing of the Gunn-Peterson trough. Assuming a neutral IGM with uniform density, the Gunn-Peterson optical depth is $\tau_{GP} = 2.1\times 10^5\,[\Omega_b h(1-Y)/0.03]\,[(1+z)/6]^{3/2}$ (where Y is the primordial helium abundance). The optical depth at a wavelength $\Delta\lambda$ to the red of the Lyα line is

$$\tau(\Delta\lambda) = \frac{\tau_{GP}\,R_\alpha}{\pi}\int_{\Delta\lambda/\lambda}^{\infty}\frac{dx}{x^2+R_\alpha^2} = \tau_{GP}/\pi\,\arctan\left[R_\alpha(\Delta\lambda/\lambda)^{-1}\right]\ , \tag{1}$$

where $R_\alpha = \Lambda/(4\pi\nu_\alpha) = 2.02\times 10^{-8}$, $\Lambda = 6.25\times 10^8\,\mathrm{s}^{-1}$ is the decay constant for the Lyα resonance, and $\nu_\alpha = 2.5\times 10^{15}\,\mathrm{Hz}$ is the frequency of the Lyα line. This expression can be approximated to

$$\tau(\Delta\lambda) = \tau_{GP}R_\alpha/\pi(\Delta\lambda/\lambda)^{-1} = 1.3\times 10^{-3}\,[\Omega_b h(1-Y)/0.03][(1+z)/6]^{3/2}(\Delta\lambda/\lambda)^{-1}\ . \tag{2}$$

This width of the damped absorption from the IGM is of similar breadth as the emission lines we may expect from starburst galaxies, so the red side of the Lyα emission line should be partially suppressed by the IGM in a galaxy observed before the reionization. It is possible that the ionizing radiation of the galaxy itself would have ionized the surrounding IGM, but this is unlikely in a source with a strong Lyα emission line because most of the ionizing photons need to be absorbed to produce the line. The edge of the Gunn-Peterson trough should have the shape given by equation (2), except for the fact that the inhomogeneity of the IGM may alter the profile (in

particular, the presence of a halo of gas accreting on the galaxy may substantially increase the column density contributing to the damped profile from gas at a redshift close to that of the galaxy). This damping wing is studied in more detail in Miralda-Escudé (1997).

5. Effect of the Population B on the Faint Galaxy Number Counts

We have calculated in this paper that the galaxies where the heavy elements observed in the Lyα forest at $z \simeq 3$ were synthesized have to contribute a mean surface brightness of $32\,\mathrm{AB\,arcsec^{-2}}$ to the galaxy number counts. The majority of these galaxies should be at redshifts higher than any galaxy redshifts determined so far ($z \gtrsim 5$), due to two reasons: first, it is unrealistic that the massive stars could have formed in a highly synchronous fashion, shortly before the redshift where the heavy elements are observed; and second, the dispersion of the heavy elements through the Lyα forest should take a substantial fraction of a Hubble time, because the enriched gas is not likely to be expelled from the halos around galaxies at a velocity much higher than the escape speed.

Let us now compare this predicted mean surface brightness for the Population B with the mean surface brightness of the faintest galaxies observed so far. We shall do this in the I and K bands. In the I band, the faintest galaxies in the HDF are at $I \simeq 28.5$, reaching a number density at this magnitude of $5 \times 10^5\,\mathrm{deg^{-2}\,mag^{-1}}$ (Williams et al. 1996). The slope of the counts at this magnitude is ~ 0.2 (meaning that the counts are increasing as $10^{0.2I}$). If we assume that this slope remains constant at all fainter magnitudes, the total mean surface brightness from galaxies with $I > 28.5$ is $31.2\,\mathrm{AB\,arcsec^{-2}}$. Because this is only a factor 2 brighter than the expected value for the Pop B galaxies, we can conclude that if all the Pop B galaxies were at $z < 6$ (and therefore still observable in the I band), then either these Pop B galaxies should be the objects detected just at the magnitude limit in the HDF, or the slope of the I counts should rise again at fainter magnitudes to a value greater than 0.4, to yield a mean surface brightness comparable to the one contributed by the galaxies with $I \sim 29$. The first possibility is probably ruled out from the work of Madau et al. (1996), who find that only a small fraction of the faint galaxies in the HDF can be at $z > 3.5$ (see their Fig. 8a).

Actually, the I counts do not need to steepen again at $I > 29$, as long as most of the surface brightness inferred for the Population B comes from galaxies with $z > 6$, since the Gunn-Peterson trough will then cause these galaxies to drop out of the I band. But the same argument can be applied at longer wavelengths as better observations become available in the J, H and K bands in the future, from HST and NGST. If the counts were observed to flatten to a shallow slope, and the mean surface brightness from the faintest observed galaxies were already less than $32\,\mathrm{AB\,arcsec^{-2}}$, while the redshifts of these galaxies were still not significantly higher than the redshift at which the heavy elements were present in the Lyα forest, then we could infer that the slope of the galaxy counts should steepen again; in other words, there should be a "second hump", a maximum in the contribution to the mean surface brighness as a function of galaxy magnitude, due to the Pop B

galaxies. The presence of a "second hump" would be evidence that the Populations A and B are really distinct, as in the cases (a) and (b) discussed in Section 2 (unless dust obscuration could cause the dip between the two "humps" in the galaxy counts).

The present observations in the K band from the ground are not yet deep enough to put significant constraints along this line of argument. The faintest counts determined so far yield a density $2.2 \times 10^5\,\mathrm{deg}^{-2}\,\mathrm{mag}^{-1}$ at $K = 26.4$ (Djorgovski et al. 1995; the AB magnitude $K = 26.4$ corresponds to $K = 23.5$ in the Johnson system). Assuming a constant slope of 0.3 for the faint counts (the observed slope in the range $23 < K < 26.4$), the mean surface brightness due to galaxies with $K > 26.4$ should be $29.2\,\mathrm{AB\,arcsec}^{-2}$, still larger by a factor ~ 10 compared to the expected value for the Population B. Thus, the Pop B galaxies could appear in the K counts at $K \gg 26.4$ without requiring a steepening of the slope.

6. Dwarf Spheroidal Galaxies: Remnants of the Population B?

If the formation of galaxies occurred indeed in two distinct populations, due to the reionization of the IGM, we might then expect that any remnants of the Population B that survive in the universe at the present time would also constitute a special morphological class of galaxies.

We propose here that the dwarf spheroidal galaxies may be such remnants. Dwarf spheroidals are galaxies with luminosities in the range $10^5 - 10^8 L_\odot$, with old stellar populations and devoid of gas. The velocity dispersion of the stars is often near $10\,\mathrm{Km\,s}^{-1}$, and the surface brightness is usually low. The mass-to-light ratios are generally much higher than expected for an old stellar population, even in the center, and they vary over a wide range. Thus, the mass is dominated by dark matter at all radii, and the inferred central dark matter densities are higher than in any other known galaxies (see Gallagher & Wyse 1994 for a review). These galaxies have only been studied in the Local Group and a few nearby clusters, owing to their low luminosity.

These characteristics are similar to what should be expected in cases (a) or (b) discussed in Section 2. In this scenario, the dwarf spheroidals would have been formed in dark matter halos with $\sigma \sim 10 - 50\,\mathrm{Km\,s}^{-1}$ during reionization. A large fraction of their gas could have been expelled in a wind, which would have caused the stars to expand adiabatically in the dark matter potential well as the central baryonic mass was lost. Most of these galaxies should then have merged into more massive systems (forming part of the spheroid population of stars in normal galaxies like the Milky Way; see MR97), but some could survive until today in orbit in galactic halos, or even have remained as isolated objects. Many dwarf spheroidals show evidence for multiple starbursts, some of them having taken place only a few billions years ago. This does not contradict our picture, but it implies that after the initial starburst at reionization, dwarf spheroidals were able to accrete more gas and undergo other starbursts at later times. This could happen when the accreted gas becomes self-shielding to ionizing radiation and cools rapidly, as in the scenario outlined by Babul & Rees (1992). Accretion of new gas should occur before these dwarfs are captured in an orbit

within more massive galactic halos, because after this capture the surrounding gas will be shocked to high temperature and will move at a high velocity relative to the dwarf spheroidal.

7. Conclusions

Our present understanding of the evolution of the IGM, of its reionization and its metal enrichment, leads to the expectation that the first galaxies in the universe were formed at very high redshifts, while the IGM was not yet fully ionized. These galaxies might have very different properties from the galaxies we are familiar with in the present universe; they affected the physical state of the intergalactic gas that later formed the more massive galaxies like the Milky Way, and the stars that formed in them are probably part of the spheroidal components in present-day galaxies. The discovery of these high-redshift galaxies is a crucial and necessary step to advance to a more complete understanding of how galaxies formed.

The requirement of having produced the density of heavy elements in the Lyα forest leads to a prediction of the mean surface brightness contributed from the Population B galaxies. This mean surface brightness is not much smaller than that due to the faintest galaxies so far detected with the HST and ground-based telescopes. Detection of these first galaxies, for reasonable estimates of their luminosities, should be possible with the proposed NGST, which is an ideal tool for the detection of star-forming galaxies at $5 \lesssim z \lesssim 20$ (Mather & Stockman 1996), using the Gunn-Peterson trough to identify them. At present, the brightest examples of galaxies at these redshifts might already be found with HST and Keck, possibly with the help of lensing magnification in the fields behind rich clusters of galaxies.

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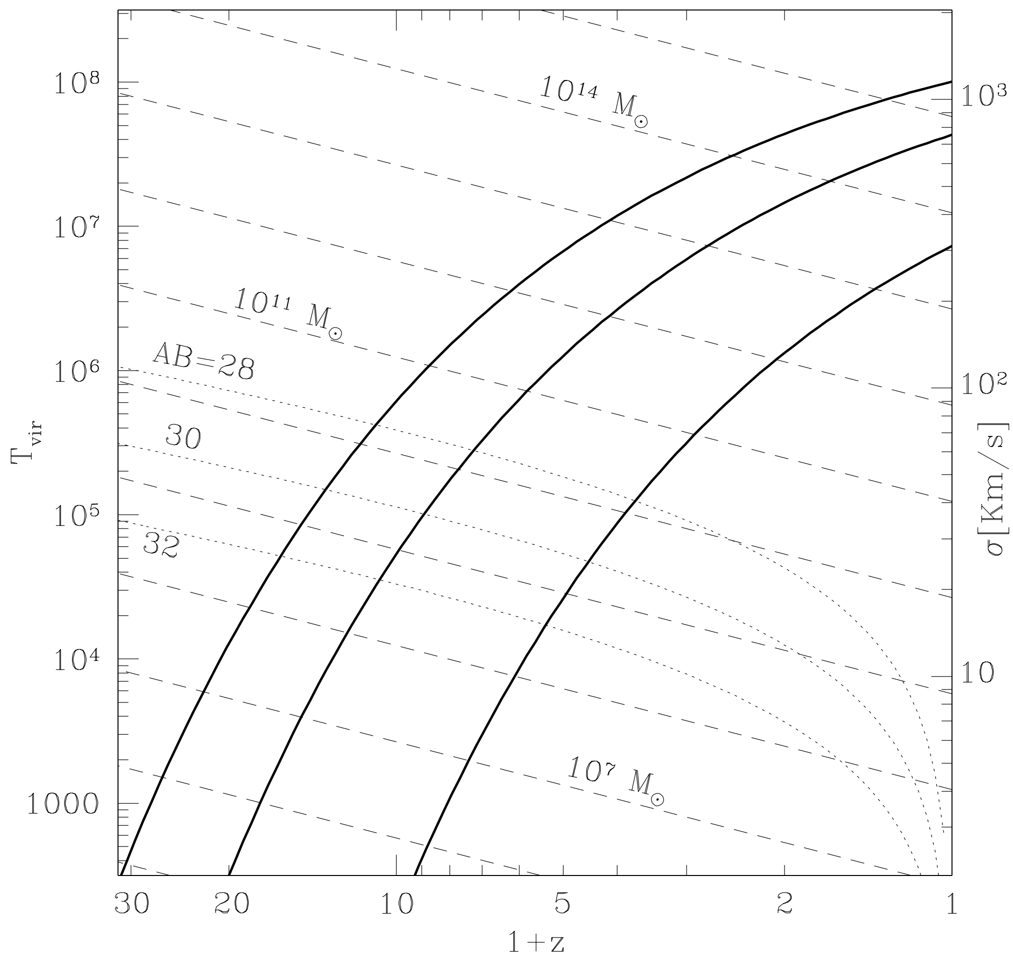

Fig. 1.— Thick solid lines give the virial temperature and velocity dispersion of halos collapsing at redshift z, for (1,2,3)-σ peaks, in the cold dark matter model with $\Omega = 1$, $h = 0.5$, $\sigma_8 = 0.7$. The dashed lines are for constant halo mass. The high-σ peaks collapse on a larger scale than the low-σ peaks at a fixed epoch, hence they have higher velocity dispersion and masses. The dashed lines give the AB magnitude of a galaxy formed in a given halo, assuming that all baryons in the halo (accounting for 8% of the total mass) turn to stars in a starburst lasting for 0.3 times the age of the universe. The AB magnitude is at a rest-frame wavelength in the UV, longward of Lyα .